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## Soft-Material Robotics

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## Abstract

There has been a boost of research activities in robotics using soft materials in the past ten years. It is hoped that the use and control of soft materials can help realize robotic systems that are safer, cheaper, and more adaptable than the level that the conventional rigid-material robots can achieve. Different from a number of existing review or position papers on soft-material robotics which mostly present case studies and/or discuss trends and challenges, the review focuses on the fundamentals of the research field. First, it gives a definition of soft-material robotics and introduces its history which dates back to the late 1970s. Second, it provides characterization of soft-materials, actuators and sensing elements. Third, it presents two general approaches to mathematical modelling of kinematics of soft-material robots i.e. piecewise constant curvature approximation and variable curvature approach, as well as their related statics and dynamics. Fourth, it summarizes control methods that have been used for soft-material robots and other continuum robots in both model-based fashion and model-free fashion. Lastly, applications or potential usage of soft-material robots are described related to wearable robots, medical robots, grasping and manipulation.



# 1

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## Introduction

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In the biological world we find structures made of soft materials everywhere, starting from leaves, bacteria and spider silks, to skins, hairs, brains, and muscles. In fact it is known that over 80% of body weight of an adult human consists of soft substances. In general, it is crucial for biological systems to have soft materials because deformation of structures is the origin of many functions necessary for their survival, such as heart deformation for circulating blood, eye lens deformation for optical focus, and muscle deformation for limb motions [Pfeifer et al., 2014].

In contrast, most of today's robots are made of rigid materials such as metals and hard plastics. The underlying reason is manifold. Rigid materials are easier to handle for conventional manufacturing technologies. They are also easier for mathematical modeling and control purposes. Also they are often more stable as materials and robust against various decays. Body articulations based on rigid parts facilitate replacement and repair if necessary. The drawback of the robots is their tendency to be highly specialized and lack of many properties owned by their natural counterparts in dealing with unstructured environments, such as adaptability, energy efficiency of safe interaction with human.

In the recent years, there has been an increasing interest in the more active use of soft materials in robotic systems. Having a soft body like the ones in biological systems can potentially provide a robot with superior capabilities. For example, soft body can help the robots to adaptively navigate through small opening, softness can prevent injuries in human-robot interaction, while deformable body can also store and release energy, which may lead to energy efficiency in locomotion tasks. As it will be shown in the review, by building robotic systems with soft materials, we are able to realize systems that are safer, cheaper, and more adaptable than the level that the conventional robots can achieve.

For this reason, there have been a number of review papers on robotics using soft materials (further detail in §1.3). Different from those papers, this review focuses on the fundamental aspects of the research field which have not been covered in depth, to give a strong foundation for understanding the essential stream of this field. In the rest of the review, we start with the characterization of soft robots and the brief history of them, which are followed by more technical chapters about materials, actuators and sensors, modeling, control, and applications.

## **1.1 What is soft-material robotics**

The term “soft-material robotics” is sometimes loosely used with “soft robotics”. The term “soft robotics” has been used in different meanings and contexts. Its definition has not been widely agreed on but it is converging. According to a review paper [Laschi and Cianchetti, 2014] and the First Working Paper released in September 2014 from the European Future and Emerging Technologies Open Coordination Action, RoboSoft <sup>1</sup>, softness may refer to both structural compliance and inherent material compliance. Thus soft robotics may be defined as robotics that encompasses solutions that interact with environment relying on inherent or structural compliance. According to a position paper [Rossiter and Hauser, 2016], soft robotics is an umbrella term that covers all

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<sup>1</sup><http://www.robosoftca.eu>

types of active and reactive compliant systems. For those interested in the part of soft robotics which deals with structural or active compliance, further information may be found in [Albu-Schaeffer et al., 2008, Verl et al., 2015] and other papers related to active impedance control [Hogan, 1985], series elastic actuators [Groothuis et al., 2014, Austin et al., 2015], and variable stiffness actuators [Pratt and Williamson, 1995, Vandebrorht et al., 2013, Austin et al., 2015].

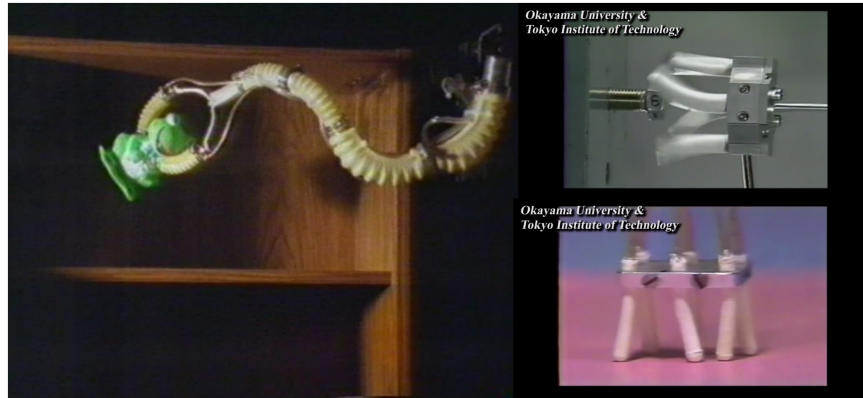
Soft-material robotics, which is the focus of the review, is the part that deals with inherent material compliance. Soft material (also called soft matter) includes liquids, polymers, foams, gels, colloids, granular materials, as well as most soft biological materials, according to the scientific journal *Nature*<sup>2</sup>. The common feature of soft material is that it consists of large molecules or assemblies of molecules that move collectively, and, as a result, it gives large, slow, and nonlinear response to small forces [Doi, 2013].

To elaborate on inherent material compliance, soft-material robotics may be defined as robotics that studies how deformation of soft material can be exploited or controlled to achieve robotic functions [Wang and Iida, 2015]. Other definitions exist [Laschi et al., 2016] but the shared keyword is “deformation”. In the case of solid soft-materials, many researchers focuses on materials with a relatively low modulus (below 1 GPa) at room temperature [Majidi, 2013, Rus and Tolley, 2015]. This excludes soft-materials such as certain thermoplastics, which have been used to build supporting structures or kinematic linkages as cheaper alternatives to metals. Since the novelty of soft-material robotics lies in deformation, technologies where other aspects (e.g. adhesion) of soft materials are exploited are also excluded (as opposed to including climbing technologies in [Laschi et al., 2016]). Furthermore, studies related to micro-robots or the so-called nano-robots are not considered here, even if soft materials such as certain biological materials are used. By doing this, we hope to define the research field more clearly and differentiate it from existing fields.

According to [Trivedi et al., 2008b, Marchese et al., 2016], soft(-material) robots are a subset of continuum robots [Robinson and

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<sup>2</sup><http://www.nature.com/subjects/soft-materials>



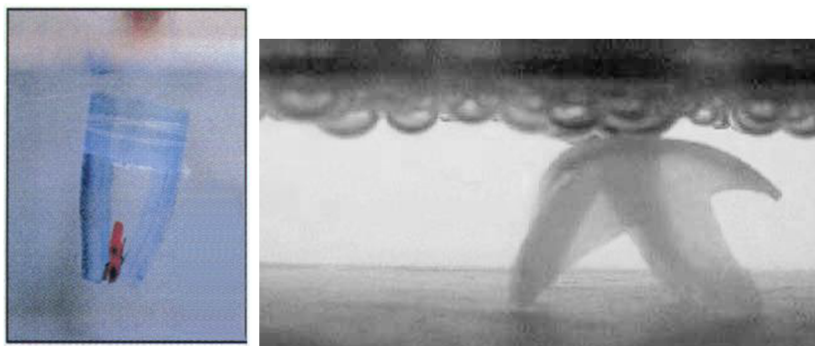
**Figure 1.1:** Early pneumatically-actuated robots with continuously-deforming air chambers or channels. Left, an arm comprised of pneumatically-actuated bellow-like segments [Wilson, 1984, Wilson and Mahajan, 1989]. Right, a hexapod and a hand whose legs and fingers were comprised of pneumatically-actuated tri-cellular segments [Suzumori et al., 1991a,b]. All figures are snapshots from videos <sup>3</sup>under Standard Youtube License.

Davies, 1999], which are a further subset of hyper-redundant robots [Chirikjian and Burdick, 1991]. However, not all continuum robots are soft and even continuum robots referred to as soft [Trivedi et al., 2008b] have varying degrees of rigidity [Marchese et al., 2016]. To the best of our knowledge, the first published paper to use the term “soft” to describe a robot is [Hirose and Umetani, 1978]. The “soft gripper” presented in that paper should be more appropriately seen as a hyper-redundant robot.

## 1.2 History of soft-material robotics

The history of soft-material robotics dates back to at least the late 1970s, when robot grippers based on granular materials were first published [Cardaun, 1978, Schmidt, 1978, Perovskii, 1980]. Recent reviews [Rus and Tolley, 2015, Laschi et al., 2016] date the history back to middle 1980s or early 1990s, which may be due to their focus on a par-

<sup>3</sup><https://www.youtube.com/watch?v=Dh7dsLCazss>,  
<https://www.youtube.com/watch?v=kHGLYRUKWeM>



**Figure 1.2:** Early robots made from gels. Left, a fingered gripper made from temperature-sensitive N-isopropylacrylamide gel and acrylamide gel [Hu et al., 1995]. Right, a legged robot made from electroactive polymer gel [Otake et al., 2000]. All figures are reproduced with permission of the copyright owners.

ticular type of soft material such as elastomers and overlooking earlier published work on other types of soft material such as granular materials. Robots based on other soft materials, such as elastomers, fluids, and gels emerged in the 1980s and 1990s.

The first piece of published work on using elastomers for a continuously-deforming body is [Wilson, 1984, Wilson and Mahajan, 1989]. The pneumatically-actuated robot arm was comprised of 4-5 bellows with two additional bellows used as grippers. Upon bending of these bellows, the arm was able to pick, move and place an irregularly shaped object (see Figure 1.1). The second piece of published work with a similar robot is probably [Suzumori et al., 1991a,b]. Instead of bellow-like units, tri-cellular units were designed and made, where the three cells are distributed about a central axis with each spanning  $120^\circ$ . With a number of these units, hands and hexapod could be made for manipulation and walking (see Figure 1.1).

The first piece of published work on using electrorheological (ER) fluid in robot grippers is [Kenaley and Cutkosky, 1989]. The first piece of published work on using gels in robot grippers is probably [Hu et al., 1995] (see Figure 1.2). Other work using gels which is worth mentioning includes the crawling robot made from electroactive polymer gel

Otake et al. [1999]. Both ER fluid and electroactive polymer gel belong to electroactive polymers (EAPs) [Bar-Cohen, 2004]. However, not all EAPs are soft-materials e.g. ionomeric polymer-metal composites may not be considered as soft-material due to the presence of metals, despite its use in robot grippers in the late 1990s.

The influences of shape, deformation, and material properties to functions and behaviors of robots have also been attracting many robotics researchers for a long time. Probably one of the earliest attempt to establish the conceptual formulations was in the context of Embodied Artificial Intelligence research [Pfeifer, 2000, 2003]. The work highlighted how control of robots is related to “morphology” of them by introducing several earlier case studies of rigid shape changing robots, with an additional notation about how the concept can be extended for soft-material robots. In the last decade, this research area was populated by a number of biologically inspired robot case studies to learn how nature takes advantage of softness and deformation for adaptive functions and behaviours [Pfeifer et al., 2007, 2014]. As discussed more details in Chapter 6, based on these bio-inspired soft robotics research, body deformation can be explained and exploited for the purposes of actuation, sensing, and computation of robots, that provides an alternative way to design and construct intelligent robots not fully relying on the conventional sensory-motor control architectures.

### 1.3 Soft-material robotics today

Today the landscape of soft-material robotics research has changed, even though the basic concepts haven’t. Technologies have been improved and made finer. [Wang and Iida, 2015] listed five probable reasons why soft-material robotics has resurfaced and gained substantial traction at the beginning of the 21st century, which has led to the branding of the research field.

- Soft material has been established as a field in material science since the 1990s.
- A large amount of new soft material has been synthesized and made commercially available.

- Diverse fabrication techniques for soft material have been invented and made accessible.
- An increasing amount of work demonstrating the use of soft material in robotics has been published in high-profile journals.
- Researchers generally agree that soft-material-based technologies should be used in robotic applications in the future as they are intrinsically cheaper, safer, and more adaptive in complex task environments as compared with the conventional rigid systems.

An important aspect lies in the fact that we are beginning to understand the boundaries of what the conventional rigid robots can and cannot do. Elegant natural motions we often encounter in very small animals to large ones, for example, cannot be realized without considering the exploitation of material dynamics and functions. The impressive work done by conventional engineers in the last decade made it explicit that there are many things rigid robots cannot do even if we push them to the limit; this in turn has led many researchers to start exploring new dimensions, especially those related to mechanical dynamics and materials.

Another aspect is that integration of essential components for a soft robot is possible because of the maturity and accessibility of individual technologies such as those for materials, actuators, sensors and electronics, etc. As a result, research has progressed towards integration of these technologies and demonstration of superior functions at the system level.

A third aspect that has progressed from decades ago is that soft-material robotics research no longer requires high cost in time and budget. Off-the-shelf technologies, including materials, sensors, motors, and prototyping machines, allow even a hobbyist to make a robot in a matter of hours with pocket money. Computational tools such as physics engines, computer vision, and high-power microprocessors also facilitate the ways younger students are becoming involved in research projects. The Internet provides countless ready-made sample programs to set a stage for the research, most of which one had to develop from scratch decades ago. This naturally allows a number of interdisciplinary

researchers, not only engineers but also chemists, material scientists, and biologists, to join the community.

To give a clear picture of the growth of the research field and to show our contribution with this review effort, we summarize eight review papers on soft-material robots and compare them to our work in Table 1.1. We only select those review papers which cover various technical aspects of a soft-material robotic system. Hence review papers on a single aspect, such as design [Manti et al., 2016], fabrication [Cho et al., 2009] and sensing [Nanshu and Hyeong, 2013] are not listed for comparison. System integration is challenging and a technological component may not work for a robotic system unless proven.

In addition to all the review papers, there have been a number of notable position papers related to soft-material robotics [Pfeifer et al., 2012, Lipson, 2013, Majidi, 2013, Kovac, 2013, Pfeifer et al., 2014, Nurzaman et al., 2014b], where opinions on principles, activities, trends and challenges are presented.



**Table 1.1:** A summary of review papers on soft-material robotic systems (in chronological order)

Reference	History	Design & material	Fabrication	Actuation	Sensing	Modelling	Control	Comments
[Trivedi et al., 2008b]	×	✓	×	✓✓	×	✓	✓	Bioinspiration, EAPs, PAMs
[Kim et al., 2013]	×	✓✓	×	✓✓	×	✓	×	Bioinspiration, three case studies
[Laschi and Cianchetti, 2014]	×	✓	✓	✓✓	×	✓	✓	-
[Bauer et al., 2014]	×	✓✓	✓	✓✓	✓✓	×	×	Energy harvester
[Rus and Tolley, 2015]	✓	✓✓	✓	✓✓	✓	✓	✓	-
[Wang and Iida, 2015]	✓	✓✓✓	×	✓✓✓	×	×	×	Categorization based on deformation and functions
[Hughes et al., 2016]	✓	✓	✓✓	✓✓	✓✓✓	✓	×	Focus on manipulation and gripping
[Laschi et al., 2016]	✓✓	✓✓	✓	✓✓	✓	✓	✓	Categorization based on functions
This review	✓✓✓	✓✓✓	×	✓✓✓	✓✓✓	✓✓✓	✓✓✓	-

# 2

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## Actuation and Sensing

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Although it is the dream of researchers to have robots made from 100% soft materials, commercially available actuators and sensors are not always made from soft materials as defined in §1.1. For example, energy sources in most actuators are made from metals; transducer parts of many actuators and sensors are made from hard plastics; signal processing electronics in most actuators and sensors are made from metals and hard plastics.

There have been a great amount of efforts to develop the so-called “soft actuators” and “flexible and stretchable electronics”, where the transducer parts are partially or fully made from soft materials<sup>1</sup>. Reviews have also been made on these component technologies, including fluidic actuators [Greef et al., 2009], electroactive polymers (EAPs) [Bar-Cohen, 2004, Bahramzadeh and Shahinpoor, 2013], and flexible and stretchable electronics [Nanshu and Hyeong, 2013].

Different from those review work on component technologies potentially useful for soft-material robotic systems, we focus on two things: First, we emphasize those actuators and sensors which have

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<sup>1</sup>Note that the term “soft sensor” has been widely used to refer to an irrelevant concept i.e. virtual sensors which are implemented by software

been proven in a soft-material robotic systems, and they may not necessarily be soft actuators or flexible and stretchable electronics. Second, we stress the importance of actuator-sensor integration. We anticipate that further progress of the research field will heavily rely on a more seamless and successful integration of these technologies.

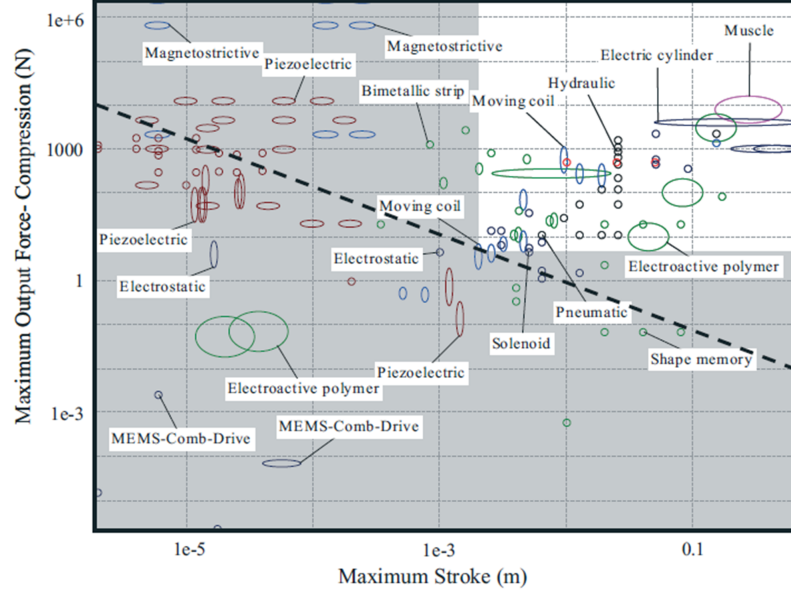
## **2.1 Actuation**

Actuation is certainly the most important technical aspect in soft-material robotics. This could be seen from Table 1.1 that all review papers have covered it to at least a moderate extent. In contrast to robots made from hard rigid kinematic linkages, soft-material robots rely on deformation of soft materials, rather than displacement of joints and rigid linkages, for motion and functions [Wang and Iida, 2015]. Hence actuation depends on the types of soft materials and their mechanical properties, among which modulus, viscosity, breaking elongation, tensile strength are the most important.

Polymers are by far the most common category of soft materials used in robotic systems. Elastomers, including silicone-based elastomer and polyurethane, are used for most of the functions. Certain thermoplastics, such as polyethylene and ethylene-vinyl acetate (EVA) are popular materials for gripping and legged or crawling locomotion. EAP gels are also used. Besides polymers, granular material and smart fluids are also used, but only for robotic gripping. Colloids are less studied, except for foam.

**Table 2.1:** Polymer mechanical properties, functions, and actuation methods [Wang and Iida, 2015]

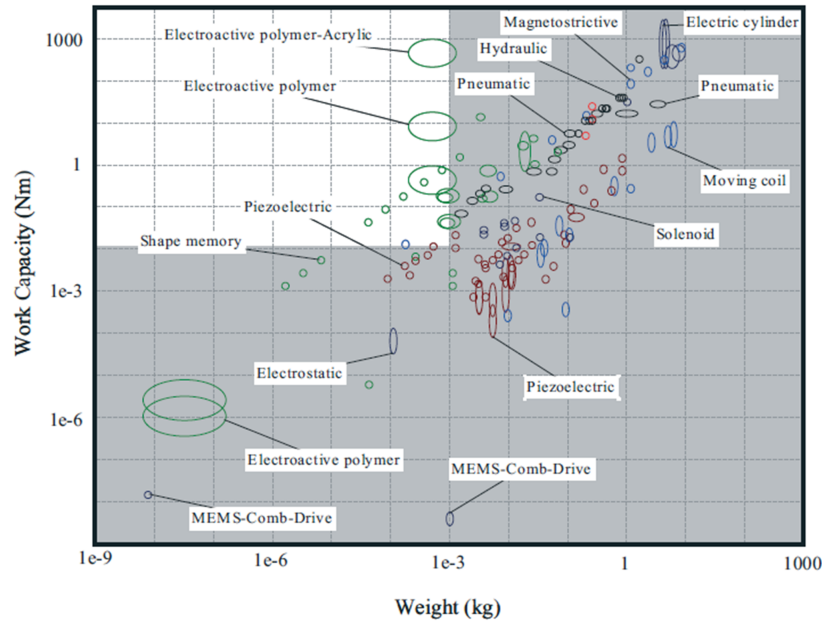
Soft material - function	Modulus (Pa)	Breaking elongation	Tensile strength (MPa)	Soft part dimension (mm)	Actuation
Silicone-reaching [Cianchetti et al., 2011]	55K-105K	800%-1000%	0.8-2.4	D: 20-30; L: 100-450	Motors cables, SMA
Silicone-handed gripping [Ilievski et al., 2011]				D: 90-140	Pneumatic
Silicone-twinning gripping [Cianchetti et al., 2011]				D: 20-30; L: 100-450	Motors cables
Silicone-legged [Shepherd et al., 2011]				139×59×5 or D: 20; L: 240	Pneumatic, motors cables
Silicone-crawling [Kim et al., 2007]	0.3M-3M	≥160%	2.2-7.7	2×2	Biological cells
Silicone-jellyfish [Villanueva et al., 2011, Nawroth et al., 2012]	0.24M-3M	160%-529%	2.2-7.7	D: 9 or 164	Biological muscle, SMA
Silicone-swimming [Herr and Dennis, 2004]		315%	1.5-2	50×12	Biological muscle
Silicone-rolling [Steltz et al., 2009, Lin et al., 2011]	0.15M-0.6M	364%-1000%	3.3-3.8	D: 30-390	SMA, pneumatic
Silicone-octopus [Sfakiotakis et al., 2013]				D: 20; L: 200	Motors cables
Polyurethane-rolling Yim and Sitti [2012]				D: 15; L: 40	Electromagnetic
EVA TPA-gripping	5M-70M	≥100%	1-5	D: 15; L: 200	Motors cables
EVA TPA-legged	5M-70M	≥100%	1-5	D: 7; L: 100	Motors cables
Polyethylene-legged [Nishida et al., 2008]	0.1G	90%	33	70	SMA
Polymer gel-gripping [Hu et al., 1995]	1K-33M	200%-2000%	0.5-5	8×2	Self-actuated
Polymer gel-swimming [Jr. et al., 2006]				70	Motor



**Figure 2.1:** Maximum output force and maximum stroke of various actuators Zupan et al. [2002]. Figure is reproduced with permission of the copyright owner.

To establish relations between actuation and material, we focus on polymers since that they are the largest group of soft material used to date. The source data were collected from previous publications and are shown in Table 2.1, in which a summary is provided for the types of materials used, mechanical properties, the types of actuators, and the types of behavioral functions demonstrated. It is assumed the materials are used under similar conditions, such as room temperature, ambient humidity, and age of materials. It is also indicated the size of the parts that are made of soft materials. In addition to the mechanical properties and size, the actuation characteristic is another important source of data necessary for the quantification of behavioral functions. Here, we specifically consider three types of actuation characteristics, i.e., mass, maximal output force, and maximal actuator stroke (Figure 2.1 and 2.2).

Tables 2.1, Figure 2.1 and Figure 2.2 may be used together for mechanical characterization of soft-material robots. For example, silicone-



**Figure 2.2:** Work capacity and mass of various actuators Zupan et al. [2002]. Figure is reproduced with permission of the copyright owner.

based elastomer Ecoflex has been used in robot parts at the centimeter scale for functions such as reaching, gripping, and legged locomotion. Ecoflex has a modulus within the range of 55-105 KPa and a breaking strain within the range of 800%-1000%. The corresponding robots were typically actuated by electromagnetic motors with cables, pneumatic actuators, or shape-memory alloys. The mass of the electromagnetic motors, pneumatic actuators, and shape-memory alloys is within the range of 0.01-1, 0.001-30, and 1e-6-1 kg, respectively; the maximal output force of the three is 1-30, 10-200, and 0.08-100 N, respectively; and the maximal stroke of the three is 0.003-0.01, 0.006-0.025, and 0.003-0.1 m, respectively.

## 2.2 Sensing

Soft-material robots require not only fundamentally novel approaches to actuation, but also to sensing. While the robot will likely need to be able to sense the environment or its own spatial configuration to accomplish its task, the sensors used must not affect the intrinsic compliance of the robots.

In order to cope with this major challenge, some studies focus on minimizing contact between sensors made of hard material and the soft substrate where they are placed. For example, a method for deflection sensing based on a LED and a photodiode is proposed to overcome the problem of the contact between the deflection sensor and the substrate which may affect the substrate's stiffness [Dobrzanski et al., 2011]. Instead of having a deflection sensor at the deflection point, the LED and the photodiode are placed onto two different planes connected at the point. Afterward, the deflection angle between the two planes is extracted from the LED light intensity detected at the photodiode. Facilitated by the ability to fabricate the sensor in small size, it is implemented to a real time shape monitoring of a 100  $\mu\text{m}$  thin, flexible polyimide substrate.

Along similar direction, another example that demonstrates the advantage of the ability to fabricate sensors made of hard material in small size for soft-material robots is shown by [Floreato et al., 2013]. Inspired by compound eye of fruit fly *Drosophila* and other arthropod species, it is shown that a miniature curved artificial compound eye occupying a volume of 2.2  $\text{cm}^3$  can be fabricated by bending a rectangular array of 42 columns of 5 microlens, whose diameter equals to 172  $\mu\text{m}$ , down to a curvature radius of 6.4 mm. Towards applications like thin wearable sensors on smart clothing or integrated in the artificial skin of soft robots, it is suggested therein that cost-effective mass production of devices that allows complex dicing to achieve various bending patterns is an important research direction.

Nevertheless, the focus of this chapter is to discuss the fundamentals and current progress of studies that focus on sensors made of soft material and their potential use in soft-material robots. The summary of the latest advances and relevant issues is shown in Table 2.2.

The first issue is the chosen soft material based on the expected sensing functionality. Polymer, including elastomer, i.e. a natural or synthetic polymer having elastic properties, is the most commonly used material. However, they are commonly combined with other materials to find the most suitable mechanical and electrical properties for the intended sensing purpose. For instance, in [Culha et al., 2014a,b] thermoplastic elastomer and carbon black particles are combined to find the desirable properties for strain sensing.

Because the sensors are soft and may be integrated with soft-material robots, important mechanical characteristic such as Young's modulus and breaking elongation must be taken into consideration and yet accommodate the desired sensing characteristics. For example, the soft strain sensor designed by [Muth et al., 2014] has lower Young's modulus than the one explained in [Culha et al., 2014a], meaning that it is less likely that it will affect the intrinsic compliance of a soft-material robot once they are integrated. However, the sensor explained in [Culha et al., 2014a] has larger Gauge factor, i.e. a small value of strain will cause larger change of the resistance of the sensor, meaning that the sensor is more sensitive to strain.

Another important issue is the dimension of the sensors, which may affect their suitable application and how they will be integrated with the robot. Regarding the integration issue, some of the sensors are 3D printable which should make them easier to integrate with soft substrates that compose the robot [Muth et al., 2014, Culha et al., 2014a]. Last but not least, some of the sensors are designed to perform proprioceptive sensing, i.e. the measurement of values internal to the system such as position [Girard et al., 2015] and experienced strain [Muth et al., 2014, Culha et al., 2014a], and others are designed to perform exteroceptive sensing, i.e. the measurement of external stimuli like temperature and other tactile information [Chen et al., 2015, Chossat et al., 2014, Buscher et al., 2015].

It is interesting to note that only the first four publications shown in Table 2.2 have demonstrated the integration of the sensors into soft-material robots, indicating integration aspect as one of the most fundamental challenges in the field.



**Table 2.2:** Summary of the latest studies on soft material sensors (note: S = sensitivity, SR = sensing range, R = resistivity, GF = gauge factor, ER = error range, R = radius, T = thickness, L = length)

Soft material - function	Modulus	Breaking elongation	Sensing characteristics	Soft part dimension (mm)	Stimuli
Dielectric elastomer - position sensor [Girard et al., 2015]		800%	S: 66 pF/mm	75 (R), 0.11 (T)	Strain
Magnetic field (MF) sensor inside silicone rubber - curvature sensing [Ozel et al., 2015]			S: $5.6 \times 10^{-4} \text{ cm}^{-1}/\text{mV}$	$50 \times 70 \times 11$	MF
Optical fibre - pose sensing [Sareh et al., 2015]	$0.06 \text{ Nmm}^{-1}$		ER: 13-18%		Light
Conductive polymers and piezoresistive stretchable knitted fabric - tactile sensor [Buscher et al., 2015]			R: 20 K $\Omega$ /m	1.5 (T), 10 (spatial resolution)	Force
Polymer and semipermeable polyurethane film - temperature sensor [Chen et al., 2015]	4.68MPa	700%	S: $0.002778 \text{ } ^\circ\text{C}^{-1}$	0.04 (T)	Temperature
Dielectric elastomer - compressive sensor [Zhang and Wang, 2016]			S: $0.91 \text{ N}^{-1}$ , SR: max. 382 KPa	0.5 mm (R), 3 mm (T)	Force
3D printable elastomer - strain sensor [Muth et al., 2014]	100K	900%	GF: 3.8	0.41 (nozzle diameter)	Strain
3D printable thermoplastic elastomer - strain sensor [Culha et al., 2014a]	2MPa	150%	GF: 20	0.158 (R)	Strain
Elastomer with embedded microchannel - multi axis force sensor [Vogt et al., 2013]	69KPa	180%	S: 28.6 - 37 mV/N	$50 \times 60 \times 7$	Force
Conducting polymer - flow sensor [Devaraj et al., 2015]			SR: 0.66 - 0.97 m/s	1 (L), 0.006 (R)	Flow
Silicone based electrodes - tactile sensor [Chossat et al., 2014]	125KPa		R: $8 \times 10^3 \Omega/\text{m}$		Force

## 2.3 Actuator-sensor integration

While the last decade has seen advances in the enabling technologies, an autonomous robot entirely made of soft material with fully embedded components remains to be seen. The closest one to an ideal case is probably the one shown by [Wehner et al., 2016], where a completely soft octopus-like robot with inflatable pneumatic compartments is shown to be able to wave its leg slowly up and down through regulated fluid flow. Nevertheless, there is no sensor device involved yet to enable the robot to autonomously response to its environment. At the other end of the spectrum, one of the examples worth mentioning is probably the work of [Yip and Camarillo, 2016], where a closed loop hybrid position/force control is enabled through the use of tension sensor made of hard material, force sensor and motion capture system in a compliant continuum manipulator.

To the authors' best knowledge, any existing soft robots either lack of components necessary to support their closed loop autonomous operation, or still use some components made of hard materials. For instance, despite demonstrating novel soft actuators, most of the works in Table 2.1 do not use sensors at all. Some of them use sensors which are made of hard material, i.e. [Lin et al., 2011] uses external sensors (i.e. motion capture system and force plate) to analyze the robot's motion, while [Yim and Sitti, 2012] and [Jr. et al., 2006] uses on-board CMOS camera and light sensor respectively.

From another perspective, despite the rapid growth in the development of soft sensors, many existing studies focus on the basic analysis of the sensors' performance without integrating the sensors with an operating soft robot. Among the examples of the latest development shown in Table 2.2, [Girard et al., 2015, Ozel et al., 2015, Sareh et al., 2015, Buscher et al., 2015] have demonstrated the integration between the sensors and with robots mainly composed of soft materials. However, a closed loop autonomy enabled by the use of the sensors are yet to be demonstrated as the work explained therein focus on characterizing the sensors' performance after their integration with the robot. In summary, Table 2.3 attempts to show the latest technological landscape of actuator-sensor integration in soft-material robots.

**Table 2.3:** Summary of the technological landscape of actuator-sensor integration soft-material robots

Reference	Types of robot	Actuation	Sensors	Hard components	Autonomy
[Wehner et al., 2016]	Octopus-like robot entirely made of soft material	Pneumatic	None	None	None
[Yip and Camarillo, 2016]	Compliant cable-driven continuum manipulator	Motors cables	Tension sensor, force sensor, motion capture system	Motion capture system (sensor), made of polypropylene (modulus: 37 Mpa)	Hybrid position/force control
[Lin et al., 2011]	Caterpillar-inspired soft-bodied rolling robot	SMA	Motion capture system, force plate	Motion capture system and force plate (sensor)	Rolling motion experiment
[Yim and Sitti, 2012]	Magnetically actuated soft capsule endoscope	Electromagnetic	CMOS camera	External magnet (actuator)	None (human-controlled)
[Jr. et al., 2006]	Swimming robot with soft tail	Motor	Light sensor	Main body of the robot	Swimming behaviors
[Girard et al., 2015]	MRI (Magnetic Resonance Imaging) guided soft polymer robot for surgical interventions	Pneumatic	Dialectric elastomer based sensor	External structure for MRI guidance (actuator)	None
[Ozel et al., 2015]	Soft snake robot	Pneumatic	Magnetic field sensor	Air compressor (actuator)	None
[Sareh et al., 2015]	Soft pneumatic continuum robot arm	Pneumatic	Optical fibre	Air compressor (actuator)	None
[Buscher et al., 2015]	Wearable tactile data-glove	Not applied	Conductive polymers, piezoresistive fabric	3D printed electronic housing, custom-built measurement rig	None

# 3

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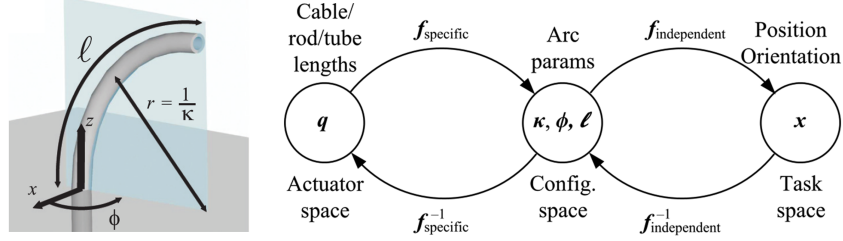
## Kinematics, Statics and Dynamics

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Previous review papers or books on soft-material robots addressed the topic of math models to a limited extent (as summarized in Table 1.1). For example, [Kim et al., 2013, Laschi and Cianchetti, 2014] concluded that most modelling work is on kinematics; [Trivedi et al., 2008b] and [Laschi and Cianchetti, 2014, Laschi et al., 2016] suggested that soft-material robots may be modelled in a similar way as a subset of hyper-redundant robots or continuum robots.

Kinematics of continuum robots is generally modelled in two ways: piecewise constant-curvature (PCC) and variable curvature (non-PCC) [Trivedi et al., 2008b, Webster and Jones, 2010, Renda et al., 2014]. Specifically for soft-material robots, [Rus and Tolley, 2015] has a brief overview of modelling with PCC approximation and [Laschi and Cianchetti, 2014, Laschi et al., 2016] briefly mentioned the use of non-PCC. Static and dynamic models of continuum robots and soft-material robots are rarer. Their modelling methods often depend on kinematic models.

PCC is simple but valid only when there are no external loads including body weight on the robot. Body weight and loading can cause significant deviations from constant curvature, leading to large tip po-



**Figure 3.1:** Piecewise constant-curvature (PCC) approximation for kinematic modelling of continuum robots. PCC enables kinematics to be decomposed into two mappings: from joint or actuator space to configuration space, and from configuration space to task space. Figures reproduced from Figure 2 and Figure 3 in [Webster and Jones, 2010].

sition error [Webster and Jones, 2010, Renda et al., 2014]. PCC also fails for modelling cable-driven robot arms due to the coupled tendon condition [Renda et al., 2014]. Non-PCC is more accurate and valid but it comes with a cost of complexity.

In this review, we use the two categories of kinematics to systematically introduce modelling methods that have been used for continuum robots and may be applied to soft-material robots. Models on statics or dynamics are introduced within each method whenever they present in the literature. Model parameters will use the original symbols as they appear in relevant publications for the ease of referencing. In case the same symbol is used for a different parameter in a different model, a footnote will be provided to avoid confusion.

### 3.1 Piecewise constant-curvature (PCC) approximation

PCC is a simplifying approach that approximates a continuum robot as a series of constant-curvature arcs. Although most continuum robots are composed of arcs that are not circular, PCC approximation has been proven useful across a variety of continuum robots. For example, in the case of a constant moment is applied along a beam, Bernoulli-Euler beam mechanics predict a constant-curvature result [Gravagne et al., 2003].

The method can also be applied to at least three types of continuum robots: those with rigid plates and continuously bending actuators, cable-driven continuum robots, and concentric-tube continuum robots [Webster and Jones, 2010]. This is because PCC enables kinematics to be decomposed into two mappings, as illustrated in Figure 3.1.

The first mapping  $f_{specific}$  is from joint or actuator space,  $\mathbf{q}$ , to configuration space with parameters that describe constant-curvature arcs<sup>1</sup>. Here actuator space may include lengths of cables, flexible push rods, or pneumatic tubes, and arc parameters may consist of triplets of curvature  $\kappa(q)$ , the angle of the plane containing the arc  $\phi(q)$ , and arc length  $l(q)$ . The mapping from actuator space  $q$  to the configuration space of arc parameters  $(\kappa, \phi, l)$  is robot-specific.

The second mapping  $f_{independent}$  is from configuration space to task space, consisting of a space curve which describes position and orientation along the backbone. The mapping is robot-independent because it is applicable to all systems that can be approximated as PCC arcs.

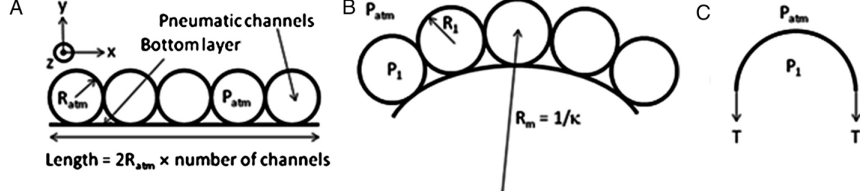
For a review of the PCC method, refer to [Webster and Jones, 2010]. Here we give detail on a special case of soft-material robots, where PCC is combined with material stress-strain relations to model kinematics and statics in pneumatic channelled soft-material appendages.

### 3.1.1 Pneumatic channelled soft-material appendages

PCC was used to model two-dimensional (2D) kinematics of curvature bending of soft bodies made of multiple channels or cells. When these channels and cells are inflated or deflated by fluids, stress-strain relation of the membrane material can give static models. The method is applicable to channels or cells with various shapes and bodies such as appendages.

[Shepherd et al., 2011] described a model for an elastomer membrane incorporating embedded fluidic channels based on a linear stress-strain relation of the elastomer for a low strain regime. Figure 3.2 shows a schematic drawing where the channels are represented by circles for analytical simplicity. The bottom layer of the membrane is unstretchable. Each of the channels is assumed to have infinite length. In Figure

<sup>1</sup>In a different context,  $\mathbf{q}$  is also used to denote a position vector in (3.13)



**Figure 3.2:** Constant-curvature bending of a soft-material body with multiple fluidic channels with circular cross-sections. Figure reproduced from Figure S5 in [Shepherd et al., 2011].

3.2A, the channels are not pressurized and the membrane is in a resting state. Figure 3.2B shows the shape of the membrane when the channels are pressurized ( $P_1 > P_{atm}$ ). The channels expand to adopt the new pressure, leading to a mismatch between the lengths of the membrane along the center of channels and along the unstretched bottom layer.

Kinematic correlation between radius of curvature of the membrane and the expansion of the channels is given by:

$$\frac{R_m}{R_m - R_1} = \frac{R_1}{R_{atm}} \quad (3.1)$$

Static relation between the expansion and the applied pressure can be derived based on the equilibrium condition for each channel, as shown in Figure 3.2C. The tensional force  $T$  per unit length along  $z$  axis along the wall of the channel is:

$$2T = 2R_1(P_1 - P_{atm}) \quad (3.2)$$

Assuming a linear stress-strain relationship for elastomers, the constitutive equation for the unit length tensional force  $T$  is <sup>2</sup>:

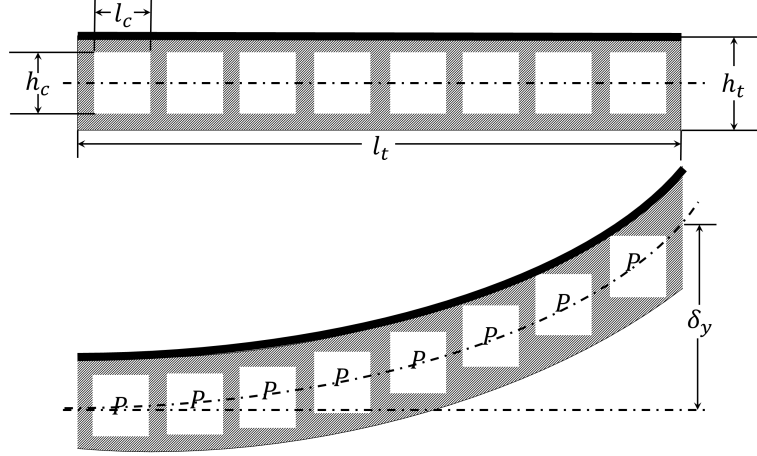
$$T = Et\epsilon \quad (3.3)$$

where  $E$ ,  $t$ , and  $\epsilon$  are the elastic modulus, thickness, and strain  $\epsilon = (R_1 - R_{atm})/R_{atm}$  respectively <sup>3</sup>. Hence,

$$\epsilon = \frac{R_{atm}(P_1 - P_{atm})}{Et - R_{atm}(P_1 - P_{atm})} \quad (3.4)$$

<sup>2</sup>In a different context,  $T$  is also used to denote an Euler angle in Figure 3.4

<sup>3</sup>In the rest of the chapter,  $t$  is also used to denote time



**Figure 3.3:** Constant-curvature bending of a soft-material body with multiple fluidic channels with rectangular cross-sections. Figure based on Figure 2 in [Onal et al., 2017].

The ratio between radii of the inflated and the original channels is then:

$$\frac{R_1}{R_{atm}} = 1 + \epsilon = \frac{Et}{Et - R_{atm}(P_1 - P_{atm})} \quad (3.5)$$

[Onal et al., 2017] also presented a model of the total bending angle and displacement of an appendage with a number of channels (see Figure 3.3). It considers channels with rectangular cross-sections and a non-linear stress-strain relation.

Applied pressure  $P$  inside the fluidic channels with height  $h_c$  and length  $l_c$  creates axial stresses  $\sigma_x$  in the material with height  $h_t$  and length  $l_t$ :

$$\sigma_x = P \frac{h_c}{h_t - h_c} \quad (3.6)$$

The resulting strain  $\epsilon_x$  is a nonlinear function of the induced stresses. The total axial deformation  $\delta_x$  of the material is the com-



bination of the individual expansions of  $n$  cells <sup>4</sup>:

$$\delta_x = nl_c \epsilon_x(\sigma_x) \quad (3.7)$$

The elastomer is constrained by an inextensible thin sheet on one side, which causes bending. The total bending angle  $\theta$  can be calculated as:

$$\theta = 2n \arctan \frac{l_c \epsilon_x(\sigma_x)}{2h_c} \quad (3.8)$$

The total out-of-plane displacement  $\delta_y$  under these conditions is:

$$\delta_y = \frac{l_t}{\theta} (1 - \cos \theta) \quad (3.9)$$

[Marchese et al., 2014b] extended the above model to include variable cell height as well as radial stress. It is important to note that this simplifying static model assumes that channels deform purely by extending their side and top walls, and that these wall stresses are based on initial channel geometry. For this reason, this analytic model is most valid for small deformations, that is, when pressure is low and the actual stresses approximate those calculated from initial channel geometry. As per the assumption of PCC, the model ignores external forces.

## 3.2 Variable-curvature (non-PCC)

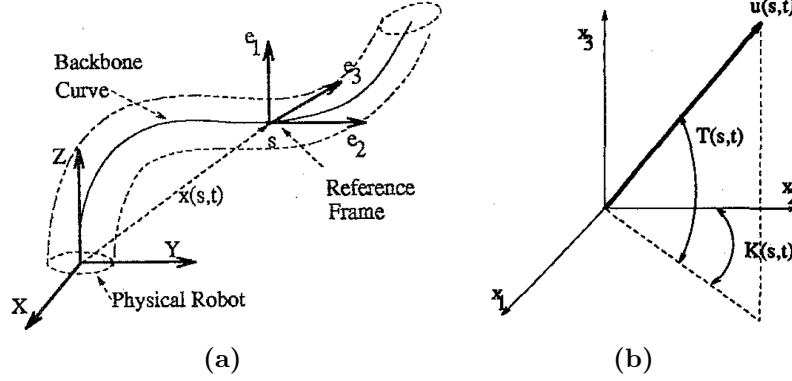
Non-PCC methods belong to three categories [Renda et al., 2014]: continuum approximation of hyperredundant systems, the spring-mass model, and the Cosserat geometrically exact approach.

### 3.2.1 Backbone continuum approximation

The method was initially developed for hyper-redundant robot manipulators [Chirikjian and Burdick, 1991, Chirikjian, 1994, Chirikjian and Burdick, 1995]. Since it is approximated as a continuum, it may be used for modelling 2D and 3D kinematics and dynamics of soft robot appendages. The method is based on the assumption that the important

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<sup>4</sup>In a different context,  $n$  is also used to denote an internal force in Figure 3.7



**Figure 3.4:** Backbone continuum approximation. (a) Reference frames. (b) Euler angles for unit tangent vector. Figures reproduced from Figure 1 and Figure 2 in [Chirikjian and Burdick, 1995]

macroscopic features of the continuum approximation can be captured by a backbone curve and associated set of reference frames which evolve along the curve.

As shown in Figure 3.4a, the position of backbone curve points can be represented in the form:

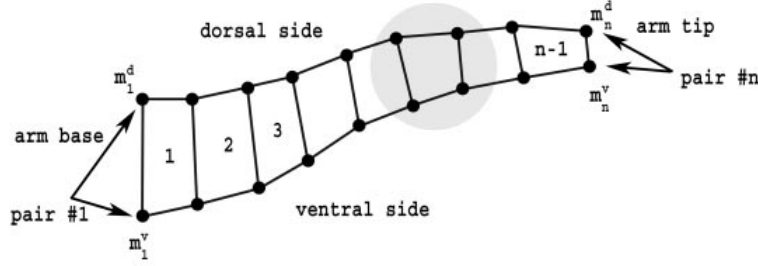
$$\vec{x}(s,t) = \int_0^s l(\tau,t) \vec{u}(\tau,t) d\tau \quad (3.10)$$

where  $s \in [0,1]$  is a dimensionless parameter that measures distance along the backbone curve at time  $t$ .  $s$  is the normalized arc length of the backbone curve in a fixed reference state at time  $t_0$ . The normalized arc length at  $t \neq t_0$  may differ from  $s$  due to elongation or contraction of the backbone curve.

The backbone curve base is located at  $s = 0$ .  $\vec{x}(s,t)$  is a vector from the backbone curve base to the backbone curve point at  $s$ .  $\vec{u}(\tau,t)$  is the unit tangent vector to the curve at  $s$ .  $l(s,t)$  is the length of the curve tangent. The associated backbone curve may be inextensible or extensible. In the extensible case, the true arc length,  $L$ , at time  $t$  is related to  $l(s,t)$  via:

$$L(s,t) = \int_0^s l(\tau,t) d\tau \quad (3.11)$$

otherwise,  $L(s,t) = s$ .



**Figure 3.5:** A 2D model of a soft-bodied appendage which consists of pairs of point masses and connecting damped springs. Figure reproduced from Figure 1 in [Yekutieli et al., 2005].

One of the possible ways to parametrize  $\vec{u}(s, t)$  is:

$$\vec{u}(\cdot) = [\sin K(\cdot) \cos T(\cdot), \cos K(\cdot) \cos T(\cdot), \sin T(\cdot)]^T \quad (3.12)$$

where  $K(\cdot)$  and  $T(\cdot)$  are Euler angles as shown in Figure 3.4b<sup>5</sup>. The kinematics of planar curves is a special case where  $T(s, t) = 0$ .

Dynamics can be approximated based on the above kinematic representation of backbone curves. Several conservation laws need to be obeyed which include mass balance, momentum balance, and angular momentum balance. For further detail on dynamic modelling based on this method, please find detail in [Chirikjian, 1994].

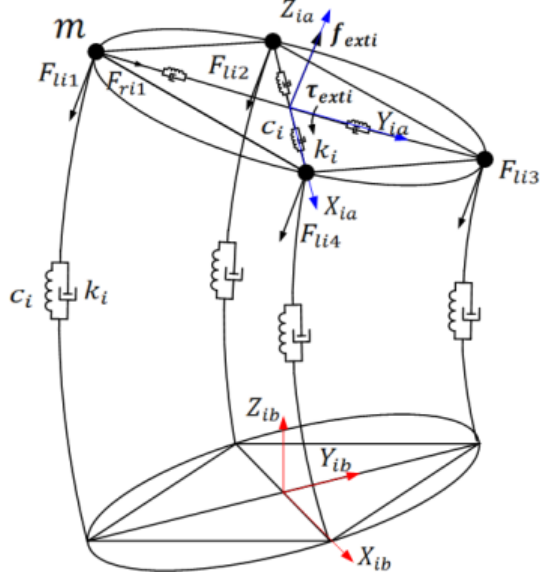
### 3.2.2 Point-mass and massless-spring with Newton's second law

By applying Newton's second law to point masses and massless springs, we can model 2D and 3D dynamics of soft-bodied appendages.

[Yekutieli et al., 2005] modelled an octopus arm as a 2D array of point masses and massless muscles as spring-damper elements (Figure 3.5). The  $2n$  masses are arranged in pairs, each consisting of one ventral and one dorsal mass. Every two adjacent pairs of masses and their corresponding muscles enclose a quadrilateral compartment. The constant volume constraint is enforced locally in each of the  $n - 1$  compartments.

Four types of forces act on the masses: 1) The internal forces generated by the arm muscles ( $\mathbf{F}_m$ ). 2) The vertical forces resulting from the

<sup>5</sup>In a different context,  $T$  is also used to denote tension in Figure 3.2



**Figure 3.6:** A 3D model of a soft-bodied appendage which consists of point masses and connecting damped springs. Figure reproduced from Figure 3 in [Zheng et al., 2012].

combined influences of gravity and buoyancy ( $\mathbf{F}_g$ ). 3) The drag produced by arm motion through the water ( $\mathbf{F}_w$ ). 4) The internal forces responsible for maintaining the constant volume constraints ( $\mathbf{F}_c$ ).

The equation of motion (EOM) can be derived from Newton's second law:

$$\mathbf{M}\ddot{\mathbf{q}} = \mathbf{F}_m + \mathbf{F}_g + \mathbf{F}_w + \mathbf{F}_c \quad (3.13)$$

where  $\mathbf{M}$  is a diagonal mass matrix and  $\mathbf{q}$  is the position vector<sup>6</sup>.

While  $\mathbf{F}_g$  is trivial and  $\mathbf{F}_m$  and  $\mathbf{F}_w$  can be defined,  $\mathbf{F}_c$  cannot be directly determined. The constraint force vector  $\mathbf{F}_c$  must be derived indirectly from the constant volume constraints. Assuming a linear function:

$$\mathbf{F}_c = \mathbf{C}\mathbf{p} \quad (3.14)$$

<sup>6</sup>In a different context,  $\mathbf{q}$  is also used to denote the actuator space in Figure 3.1

The result of the derivation is the pressure vector  $\mathbf{p}$ :

$$\mathbf{p} = (\mathbf{GM}^{-1}\mathbf{C})^{-1}[\gamma - \mathbf{GM}^{-1}(\mathbf{F}_m + \mathbf{F}_g + \mathbf{F}_w)] \quad (3.15)$$

Definition and detailed derivation of the matrix  $\mathbf{G}$  and the vector  $\gamma$  can be found in [Yekutieli et al., 2005].

[Zheng et al., 2012] extended the above 2D model into 3D. As shown in Figure 3.6, the model has four point masses attached to each cross-sectional planes, and the muscles are modeled as spring-damper elements. Each plane and the four connecting longitudinal spring-damper elements form a segment or compartment. The radial spring-damper elements act dynamically on the axis of the upper plane. The model also includes the aforementioned four types of forces.

For the  $j$ th longitudinal spring-damper element at the  $i$ th segment, the EOM can be obtained as follows:

$$\begin{aligned} m\ddot{L}_{ij} + c_i\dot{L}_{ij} + k_i(L_{ij} - L_{i0}) = & F_{lij} + \mathbf{f}_{\text{ext}\mathbf{i}} \cdot \mathbf{e}_{l\mathbf{ij}} + \|\tau_{\text{ext}\mathbf{i}}\|/\|\mathbf{r}_{\mathbf{ij}}\| \\ & + \mathbf{f}_{\text{hyd}\mathbf{i}} \cdot \mathbf{e}_{l\mathbf{ij}} + F_{islij} + \mathbf{f}_b \cdot \mathbf{e}_{l\mathbf{ij}} + \mathbf{f}_g \cdot \mathbf{e}_{l\mathbf{ij}} \end{aligned} \quad (3.16)$$

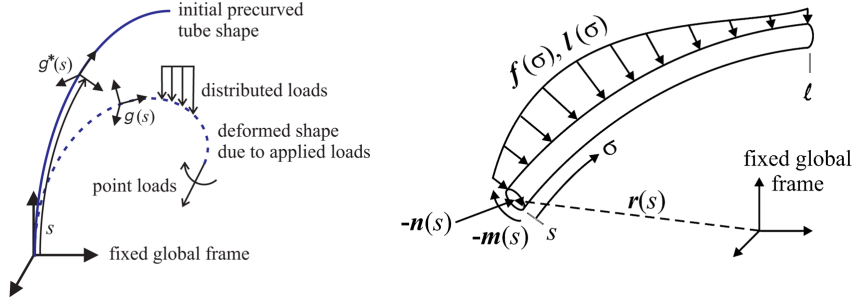
where  $L_{i0}$  is the original length of the element,  $F_{lij}$  is the force produced by longitudinal spring-damper element,  $F_{islij}$  is the force produced by isovolumetric property,  $\mathbf{f}_{\text{ext}\mathbf{i}}$  is the component force vector acting on the longitudinal elements from the upper plane,  $\tau_{\text{ext}\mathbf{i}}$  is the external torque acting on this segment,  $\mathbf{f}_{\text{hyd}\mathbf{i}}$  is the hydrodynamic force vector applied to the segment,  $e_{lij}$  is the unit vector of longitudinal elements,  $\mathbf{r}_{\mathbf{ij}}$  is the unit vector of radial elements, and  $c_i$  and  $k_i$  are the damping and stiffness coefficients.  $\mathbf{f}_b$  and  $\mathbf{f}_g$  are the buoyancy and gravity forces. All of the vectors are expressed in the base frame coordinates ( $\mathbf{X}_{\text{ib}}\mathbf{Y}_{\text{ib}}\mathbf{Z}_{\text{ib}}$ ) in this segment.

For the  $j$ th radial actuator at upper plane of the  $i$ th segment, the EOM can be obtained as follows:

$$m\ddot{R}_{ij} + c_i\dot{R}_{ij} + k_i(R_{ij} - R_{i0}) = F_{rij} + F_{isrij} \quad (3.17)$$

where  $R_{i0}$  is the original length of the element,  $F_{rij}$  is the force produced by radial spring-damper elements and  $F_{isrij}$  is the force produced by isovolumetric properties.

For kinematic models of the 2D and 3D cases, please refer to [Yekutieli et al., 2005, Zheng et al., 2012].



**Figure 3.7:** Figure reproduced from Figure 2 and Figure 3 in [Rucker et al., 2010].

### 3.2.3 Cosserat rod geometrically exact approach

Cosserat rod theory, also called geometrically exact theory of beams in finite deformation, has been used to model 3D kinematics and dynamics of continuum robots. The method was applied to at least three types of continuum robots: those with rigid plates and continuously bending actuators [Trivedi et al., 2007, 2008a], concentric-tube continuum robots [Dupont et al., 2010, Rucker et al., 2010], and cable-driven soft-bodied robots [Renda et al., 2012, 2014].

As shown in Figure 3.7, the configuration of a beam at a certain time is kinematically characterized by a position vector  $r^*(s)$  and a material orientation matrix  $R^*(s)$ , where  $s \in [0, l]$  and  $l$  is the total length of the robot appendage. The configuration space is defined as a functional space of curves  $g^*(s)$ , with

$$g^*(s) = \begin{bmatrix} R^*(s) & r^*(s) \\ 0 & 1 \end{bmatrix} \quad (3.18)$$

A local curvature vector is obtained

$$u^*(s) = (R^{*T}(s) \partial R^*(s) / \partial s)^\vee \quad (3.19)$$

where the  $\vee$  operator denotes conversion of an element of the Lie algebra to its corresponding element. The  $\wedge$  operator denotes the inverse operation. The original arc-length-parameterized curve could be

reconstructed by integrating  $\partial g^*(s)/\partial s = g^*(s)\hat{\xi}^*(s)$ , where  $\xi^*(s) = [e_3^T, u^{*T}(s)]^T$  and  $e_3 = [0, 0, 1]^T$ .

Deformation from an initial state  $g^*(s)$  to a new state  $g(s)$  can be described by change from  $\xi^*(s)$  to  $\xi(s)$ . The deformed backbone shape of  $g(s)$  is then defined differentially by  $\partial g(s)/\partial s = g(s)\hat{\xi}(s)$ , where  $\xi(s) = [e_3^T, u^T(s)]^T$ , or equivalently

$$r(s) = R(s)e_3, \frac{\partial R(s)}{\partial s} = R(s)\hat{u}(s) \quad (3.20)$$

Regarding dynamics, a cantilevered precurved rod subject is considered to an arbitrary combination of distributed forces  $f(s)$  and moments  $l(s)$  along its length, as shown in Figure 3.7. For a section at an arbitrary arc-length location  $s$ , we denote the internal force and moment, which the material of  $[s, l]$  exerts on the material of  $[0, s]$ , as  $n(s)$  and  $m(s)$  respectively<sup>7</sup>. Summing the forces on the portion  $[s, l]$ :

$$\int_s^l f(\sigma)d\sigma - n(s) = 0 \quad (3.21)$$

Taking the derivative with respect to  $s$ :

$$\dot{n}(s) + f(s) = 0 \quad (3.22)$$

Summing the moments on the portion  $[s, l]$  about the world frame origin:

$$\int_s^l (r(\sigma) \times f(\sigma) + l(\sigma))d\sigma - m(s) - r(s) \times n(s) = 0 \quad (3.23)$$

Taking the derivative with respect to  $s$  and substituting (3.22) into it yields

$$\dot{m}(s) + \dot{r}(s) \times n(s) + l(s) = 0 \quad (3.24)$$

Detailed models are formulated in [Rucker et al., 2010, Renda et al., 2014].

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<sup>7</sup>In a different context,  $n$  is also used to denote the number of cells in (3.7) and (3.8)

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## Control of Soft-Material Robots

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Classical robotic systems are generally developed for industrial automation with the expectation of accomplishing repetitive task in a static environment. They are designed and built based on the assumption that robots are kinematic chains of rigid links, connected by joints with motor driven actuators for powerful, quick and precise position control with a limited number of degrees-of-freedom (DOF). Feedback systems are commonly implemented to control a robot's behaviour by adjusting the controlled variables with respect to certain references.

Control techniques designed for robots with rigid links that assume high control authority will no longer be implementable for soft-material robots. New methods need to be proposed due to a variety of challenges [Lipson, 2013], [Culha et al., 2014a], [Pfeifer et al., 2014]. Soft-material robots have elastic and a large number of or even infinite DOF with continuum bodies, which may not have clear separation between components such as sensors, actuators, and supporting structures. Moreover, the use of soft material will make the robot more sensitive to external force, lag times and other disturbances (refer to §1.1).

As summaried in Table 1.1, previous review papers on soft-material robots addressed the topic of control to a limited extent [Trivedi et al.,



2008b, Laschi and Cianchetti, 2014, Rus and Tolley, 2015, Laschi et al., 2016]. [Rus and Tolley, 2015] identified four levels of control including low-level, inverse kinematics, dynamic operations, and planning. We agree with them on the first three levels of control, while we think motion planning is a different but closely linked concept to control.

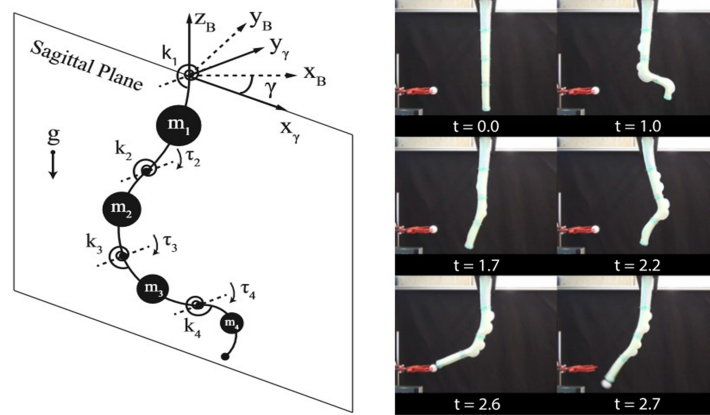
For low-level control, [Rus and Tolley, 2015] gave a brief summary of pressure control using pressure transducers or volume control using strain sensors. For inverse kinematics and dynamic operations, [Laschi and Cianchetti, 2014] included a model-based closed-loop control of a cable-driven octopus-like soft-material appendage [Giorelli et al., 2012] and a model-free control of a simulated conical-shape appendage by training an artificial neural network (ANN) [Giorelli et al., 2013]. [Rus and Tolley, 2015] included a model-based open-loop control of a pneumatic soft-material appendage Marchese et al. [2016].

In this chapter, the control approaches are divided into two large categories. The first can be denoted as a model-based approach. While modeling a soft body is not trivial as shown in Chapter 3, there are approaches where models have been used for building a particular controller. The second approach is a model-free approach. For each category, there are also open-loop control and closed-loop control. By using the classification similar to the one in [Rus and Tolley, 2015], we focus on two levels of control i.e. inverse kinematics and dynamic operations. Low-level control will not be covered due to its relatively more straightforward nature.

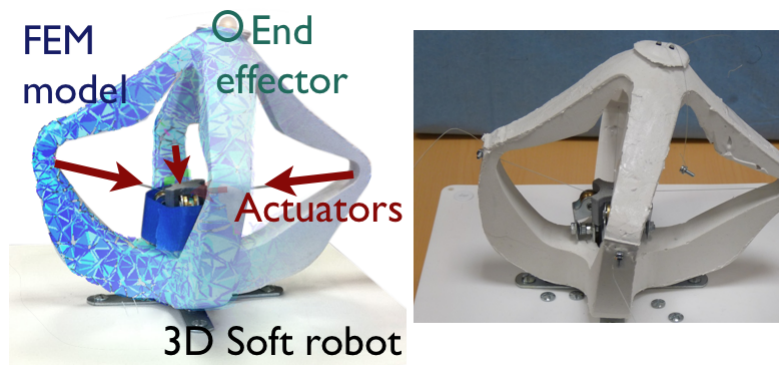
## **4.1 Model-based approach**

### **4.1.1 Model-based open-loop control**

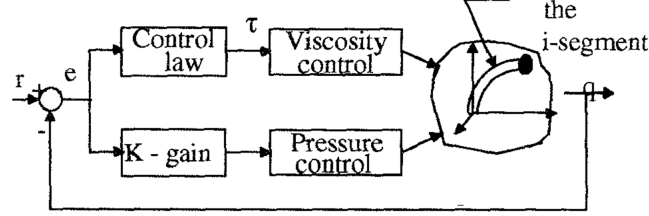
There have been a few model-based open-loop control studies for soft-material robots. [Marchese et al., 2016] developed a 3D dynamic model for a soft-material appendage by deriving EOM using Lagrangian for each segment. The dynamic model assumes PCC kinematics (refer to §3.1). After system identification in which values for unknown parameters were determined, the model was used for a controller involving iterative learning to control the position of the pneumatically-actuated



**Figure 4.1:** Open-loop control of a pneumatically-actuated soft-material appendage based on a 2D dynamic model. Figure is reproduced from Figure 1 and Figure 3 in [Marchese et al., 2016].



**Figure 4.2:** Open-loop control of a soft-material robot based on a 3D finite element model. Figure is reproduced from Figure 4 in [Driez, 2013].



**Figure 4.3:** A block diagram for model-based closed-loop control of fluidically-actuated soft-material appendages. Figure is reproduced from Figure 4 in [Ivanescu and Stoian, 1995].

soft-material appendage (Figure 4.1). The method achieved an error within 0.1 m.

[Duriez, 2013] used a real-time finite element modelling (FEM) method instead of developing models for specific robots. The FEM-based simulation computes the nonlinear deformations of the robots within 30 ms. A reduced compliance matrix is built in order to deal with the necessary inversion of the model. Then, an iterative algorithm uses this compliance matrix to find the contribution of the actuators that will deform the structure so that the terminal end of the robot follows a given position (Figure 4.2).

#### 4.1.2 Model-based closed-loop control

Many model-based studies used a closed-loop control with sensory feedback. In fact, one of the earliest studies in fluidically-actuated soft-material robots with a continuously-deforming body [Suzumori et al., 1991a,b] used a kinematics model and a K-gain feedback controller to control the end tip point position of a appendage in the vertical sagittal plane. A LED was attached to the tip of the appendage and tracked by a position measuring instrument to provide feedback. Figure 4.3 gives a representative block diagram for model-based closed-loop control of fluidically-actuated soft-material appendages.

Other representative studies on model-based closed-loop control of soft-material robots exist. [Giorelli et al., 2012] used a geometrically

exact kinematic model (refer to §3.2.3) and a control approach based on Jacobian method for end point position control of a cable-driven soft-material appendage in the vertical sagittal plane. Two force sensors and video recording were used to provide feedback on cable tensions and position of the tip of the appendage. [Wang et al., 2013] used a PCC kinematic model (refer to §3.1) and visual servoing based on a depth-independent image Jacobian matrix to control the end-point position of a cable-driven soft-material appendage. An onboard camera was used to provide feedback. [Marchese et al., 2014a, Marchese and Rus, 2016] used a PCC kinematic model and a PD-PID cascade feedback controller to control the position of a pneumatically-actuated soft-material appendage in the vertical sagittal plane. A marker-based motion capture system was used to provide feedback. [Morrow et al., 2016] used an empirical piecewise-linear model that relates pressure, force and curvature and a PID feedback controller to control force and position of a pneumatically-actuated soft-material appendage. Force and strain sensors based on eGaIn were used to provide feedback.

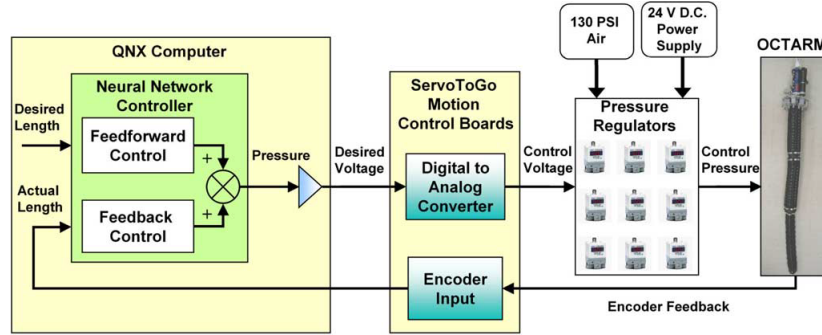
Model-based closed-loop control has also been suggested for other continuum robots [Gravagne et al., 2003, Camarillo et al., 2009, Xu et al., 2013, Roesthuis et al., 2013]. They may be potentially useful for control soft-material robots.

## 4.2 Model-free approach

### 4.2.1 Model-free open-loop control

Model-free open-loop control has been mainly used for low-level control of soft-material robots involving valves. Because this existing work does not derive control policies from nonlinear dynamic models these approaches cannot efficiently plan motions for novel tasks without sufficient manual trial and error.

An exception is universal grippers based on jamming of granular materials. Due to the ability to exhibit possibly infinite variations of postures and configurations, they can conform with objects of unknown size and shapes with simple open-loop control. These robots use model-free open-loop valve sequencing to control body-segment bending. That



**Figure 4.4:** Artificial neural network controller for a continuously-deforming soft-material robot appendage with PAMs and rigid end plates. Figure is reproduced from Figure 2 in [Braganza et al., 2007].

is, a control valve is turned on for a pre-determined duration to pressurize and then off to either hold or deflate the actuator [Marchese et al., 2016].

The review won't go into detail due to their straightforward nature for control, but will discuss it further in Chapter 6 in the context of morphological computation. For a summary of model-free open-loop control, please refer to [Marchese et al., 2016].

#### 4.2.2 Model-free closed-loop control

A few case studies attempted model-free closed-loop control of soft-material appendages. All these case studies were based on ANNs. [Braganza et al., 2007] used an ANN to control the position of a continuously-deforming soft-material robot appendage with PAMs and rigid end plates. The dynamic model of the robot was unknown. Nine string encoders were used to provide feedback. The block diagram and the robot is shown in Figure 4.4. [Kuwabara et al.] used an echo state neural network to control a simulated soft-bodied appendage. Inspired by octopus, two layers of control were proposed including central nervous system (CNS) and peripheral nervous system (PNS). CNS only sends an initiation command to PNS to adjust the base angle or send a global parameter to initiate the bend propagation, and the rest of

the required control of the arm muscles is handled by the PNS. The controller was further implemented in a continuously-deforming soft-material robot appendage with PAMs and rigid end plates [Kang et al., 2013], where a motion capture system provided feedback. [Giorelli et al., 2013]) also used an ANN to control a simulated soft-bodied appendage whose simulation is based on a dynamic model.

Model-free closed-loop control has also been suggested for a cable-driven continuum robot [Yip and Camarillo, 2016]. A force sensor, tension sensors and a camera were used to provide feedback on contact, cable tension and end point position. An optimal controller was used to control the position and force of the continuum robot. The study may be useful for control of soft-material robots too.

# 5

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## Applications

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The use of soft material with high deformability and conformability promises various applications ranging from surgical robotics to safe human robot interaction. This chapter will summarize the current advances from application perspective, meaning that it will highlight research efforts which focus on bringing soft robotics to application level, as well as emerging start-up companies offering soft robotics technologies to solve real world problems. Here, several application areas benefited by the relevant concepts and technologies will be surveyed and discussed, namely wearable robotics, medical and surgical robotics, human robot interaction, soft robotic grippers and robotic locomotion <sup>1</sup>.

### 5.1 Wearable robotics

Wearable robots can be generally defined as a machine that can be worn by human to assist them in performing particular tasks and therefore designed after the shape and function of the human body. The field of wearable robotics have grown rapidly in recent years and have demonstrated their ability to assist humans in medical, military or industrial

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<sup>1</sup><http://www.stiff-flop.eu/index.php/en/>



**Figure 5.1:** Several potential application areas of soft-material robots (from left, clockwise): soft wearable robots for rehabilitation and assistive purpose [Asbeck et al., 2014], a concept of a pneumatic granular jamming integrated actuator for surgical operations [Jiang et al., 2014], soft robotic hand mounted to the wrist of a Baxter robot for picking up various objects [Homberg et al., 2015] and a multigait soft robot able to go through small opening for applications like search and rescue [Shepherd et al., 2011]. Figures are reproduced with permission of the copyright owners.

applications. Several iconic examples include HAL (Hybrid Assistive Limb), a full body exoskeleton whose function is to assist physically challenged persons to move by enabling them to exert bigger motor energy than usual <sup>2</sup>, or HULC (Human Universal Load Carrier), intended to help soldiers in combat to carry their loads for extended periods of time <sup>3</sup>.

Nevertheless, current wearable robots rely on the use of rigid links, presenting several challenges that often disrupts the natural biomechanics of the wearer. For example, rigid links resist the movement of biological joints if they are not perfectly aligned, have large inertia, and may require bulky self-aligning system [Asbeck et al., 2014,

<sup>2</sup><http://www.cyberdyne.jp/english/products/HAL/>

<sup>3</sup><http://www.lockheedmartin.com/content/dam/lockheed/data/mfc/pc/hulc/mfc-hulc-pc-01.pdf>



Schiele, 2009, Stienen et al., 2009, Ergin and Patoglu, 2011, Browning et al., 2007]. In order to cope with the challenge, the use of soft 'exosuits' is proposed ([Schiele, 2009, Stienen et al., 2009, Ergin and Patoglu, 2011] (the most left figure in Figure 5.1). Exosuits are designed to be lightweight and unconstrained by external rigid structures to allow synergistic interaction with the wearers and minimize unintentional interference with their body's natural biomechanics. It has been shown that exosuit is able to assist walking by applying tensile forces to the body using textiles composed the soft wearable robots, connected to a mounted motor based spooled-webbing actuator [Asbeck et al., 2015b,a]. In order to measure the gait pattern of the wearer, the suit can also be equipped with soft hyper-elastic strain sensors [Menguc et al., 2013]. Exosuit is targeted to be used by individuals needing to carry heavy loads such as soldiers or recreational backpackers or those need assistance with walking such as the elderly or patients requiring gait rehabilitation.

Focusing on similar idea of providing assistance without restricting natural gait movements, other type of soft actuators are also proposed for developing soft wearable robots. For instance, a design and control of a wearable robotic device powered by pneumatic artificial muscle actuators is proposed for ankle-foot rehabilitation [Park et al., 2014]. The prototype is also equipped with various sensors for gait pattern analysis and experimentally demonstrated by using a linear time-invariant (LTI) controller. Pneumatic actuators are also used to develop a prototype of soft wearable robot for active therapeutic assistance to patients with neurological disorders, demonstrated in an experiment that enables compliant yet effective manipulation of fragile limbs of rats [Flores et al., 2016]. SMA (Shape Memory Alloy) has also been proposed as an actuator for soft wearable robots, particularly due to its ability to have high-displacement, e.g. a properly designed SMA can bent up to 180 degree [Villoslada et al., 2015]. Furthermore, there are also studies that focus on how to not rely on actuators and external power supplier by proposing concepts of passive exoskeleton. One of them is known as 'exotendon' concept: the use of long elastic cables span multiple joints in wearable exoskeletons which can temporarily store and transfer en-

ergy between joints [van den Bogert, 2003, van Dijk and der Kooij, 2014].

Aside from providing walking assistance, soft wearable robots have also been proposed to augment hand rehabilitation by using different kind of soft actuators [Polygerinos et al., 2015, In et al., 2015]. Representative examples include soft robotic glove with molded elastomeric cambers with fiber reinforcements is shown to be able to support a range of motion for individual fingers [Polygerinos et al., 2015], as well as 'exo-glove', a soft wearable assistive hand robot that focuses on the use of soft tendon routing system and underactuation adaptive mechanism [In et al., 2015].

## 5.2 Medical robotics

Recent studies show that one major potential application area of soft bodied robots is medical robotics, i.e. robots applied in medical science, with a large portion of them focus on robot-assisted minimally invasive surgery (MIS): surgery performed through tiny incisions instead of a large opening such that patients tend to have quick recovery times. It has been argued that most of the instruments used so far in MIS are rigid, lack of a sufficient number of degrees of freedom (DOFs), and/or are incapable of modifying their stiffness based on the performed tasks, as well as very application specific <sup>4</sup> [Cianchetti et al., 2014]. In order to cope with the challenge, efforts have been done to develop flexible surgical systems by introducing a new concept of soft and stiffness-controllable robotic manipulator [Cianchetti et al., 2014, Ranzani et al., 2015, Malekzadeh et al., 2014, Ratani et al., 2015, Gerboni et al., 2015, Ranzani et al., 2016] (see the bottom figure, second from the left, in Figure 5.1).

The concept of the soft and stiffness-controllable robotic manipulator is inspired by biological systems. More specifically, the designed manipulator is entirely composed of soft materials and aimed to have similar motion capabilities as the octopus's arm [Ranzani et al., 2015, Malekzadeh et al., 2014]. The manipulator is composed of two modules

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<sup>4</sup><http://empirerobotics.com/>

with multi-directional bending and stiffening capabilities. While traditional surgical manipulators are based on tendon driven mechanism, articulated motorized links or steerable needles, the proposed modules are based on a combination of flexible fluidic actuators with a variable stiffness mechanism based on granular jamming ([Rateni et al., 2015]). Moreover, the applicability of the concept for manipulation task in minimally invasive surgery has also been investigated [Gerboni et al., 2015, Ranzani et al., 2016].

Another application of soft bodied robots in medical robotics is robotic palpation. The term palpation itself can be defined as an intuitive examination procedure that uses the kinesthetic and tactile sensations of the examining physician [Ahn et al., 2012]. In this regard, robotic palpation becomes a major interests in recent years as it could overcome subjective palpation and tactile sensation [Ahn et al., 2011]. Recent advances show how the use of soft materials can bring benefits to robotics palpation [Inoue et al., 2014, Konstantinova et al., 2014]. Flexible sheets are used in a haptic device designed for virtual training of abdominal palpation [Inoue et al., 2014], while stress-velocity patterns during tissue probing has been characterized to improve the effectiveness of artificial tactile sensors for achieving optimal palpation behavior in soft-tissue examination and tumor localization [Konstantinova et al., 2014].

Another major application area is robotic endoscopy. An endoscope is a medical device used to look inside a body cavity or organ, while the medical procedure using any type of endoscope is known as endoscopy. The use of soft materials like artificial rubber muscles for the development peristaltic crawling robot attached to large intestine endoscope [Sfakiotakis et al., 2011], or shape memory polymer for soft elastmore in a magnetically actuated soft capsule endoscope have been recently proposed [Yim and Sitti, 2012].

Other application area include the use of a soft-material robot just above 1 mm is proposed for drug delivery in cancer therapy [Li et al., 2016]. The robot has a hybrid actuation, i.e. it consists of a layer that is employed for its locomotion in a magnetic field, and another layer that acts as a pH-responsive gel for trapping and unfolding motion of

the soft microrobot in pH-varying solution (see the top figure, second from the left, in Figure 5.1).

### 5.3 Grasping, manipulation and safe interaction

Grasping an object is probably the most frequent activities performed by a robot. In recent years, the use of soft material has been proposed for achieving flexible grasping of various objects with a wide variety of shapes, size and textures. The two widely recognized approaches are probably the one relying on granular jamming mechanism [Brown et al., 2010] and soft lithography: a technique to fabricate a pneumatically actuated robot with different chambers within the body that leads to different behavior [Ilievski et al., 2011]. Both approaches are already commercialized through start-up companies <sup>5</sup>, <sup>6</sup>. The problems of soft manipulation and grasping are also being investigated in large scale projects in Europe <sup>7</sup>, <sup>8</sup>.

There are also studies that investigate specific relevant aspects like anthropomorphism [Deimel and Brock, 2015] or modularity [Homberg et al., 2015], while others focus on the use of soft robotic gripper for specific tasks. An application focused example, is the use of soft robotic gripper to delicately manipulate and sample fragile species on the deep reef [Galloway et al., 2016] (see the top-right figure in Figure 5.1). It is rightfully argued therein that existing solutions for deep sea robotic manipulation commonly results in destructive interactions with under-sea life and therefore the use of soft technology is crucial.

Another related and important direction is safe physical human-robot interaction, which is one of the biggest challenges in human-centered robotics [Pervez and Ryu, 2008, Santis et al., 2008]. The use of soft bodied robots is a natural solution to realize a safe and dependable physical human robot interaction. One example would be a 3D printable soft skin module, designed to meet size and safety criteria appropriate for a toysized interactive robot [Kim et al., 2015a]. Here,

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<sup>5</sup><http://empirerobotics.com/>

<sup>6</sup><http://www.softroboticsinc.com/>

<sup>7</sup><http://soma-project.eu/>

<sup>8</sup><http://www.softhands.eu/>

the robotic system is also equipped with a pressure feedback controller for contact sensing and gentle grasping.

## 5.4 Robot locomotion

The importance of the use of soft material in robot locomotion has been discussed in many studies [Pfeifer and Bongard, 2006, Pfeifer et al., 2007, 2014, ?], due to their role in the stabilization of the body or coping with impact in walking. Many of them focus on musculoskeletal robotic system, meaning that the robot is composed of both hard and soft materials. For instance, the most recent and comprehensive discussion on the benefit of having compliance in musculoskeletal robotic system is presented in [Hosoda, 2016]. The key idea mentioned therein is the ability to regulate the structural compliance. Human body is compliant in a certain direction and rigid in another direction, and a person is able to control the directionality of compliance in order to prepare for impact during walking. The required structural compliance is provided through the musculoskeletal and skin structure.

In recent years, there are also studies that focus on locomotion of robots almost entirely or even exclusively made of soft materials. For instance, a pneumatically actuated soft robot composed of elastic polymers without hard internal skeleton is shown to be able to perform multigait locomotion [Shepherd et al., 2011]. Due the softness, ability to go under small opening and relatively low price, the robot can, for example, potentially be used for search and rescue applications.

There are also many studies on robots inspired by octopus. While some focus on the grasping ability [Margheri et al., 2012], others focus on their locomotion ability [Kang et al., 2012, Sfakiotakis et al., 2013, ?], or both [Calisti et al., 2011], with a potential application of underwater exploration and marine robotics. The studies on the locomotion ability can also be further divided into crawling [Kang et al., 2012] and swimming [Sfakiotakis et al., 2013, 2015].

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## Conclusions

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Soft-material robotics is today rapidly progressing, hence we are not able to give conclusive remarks about this research area. There were nevertheless many important achievements we learned from our previous investigations. In particular, for a systematic development, it is important to articulate this research area by material, modeling, control and applications, each of which contains important concepts and theories. It is essential that those who are working in this research area should know these previous achievements to avoid “re-inventing wheels”, and communicate on the basis of these knowledge. To this end, the goal of the review is to introduce the fundamental aspects of soft-material robots from history, modelling, control, and system integration. This content sets the review out away from existing review effort focusing on presenting individual case studies.

There are, on the other hand, a number of transversal issues that do not perfectly fit into the structure we are presenting in this review. Among others, it was not explicitly discussed, for example, how functions and behaviors can be generated from the soft-rigid hybrid structures that are necessary to make more scalable robotic systems. Soft structures themselves are usually not able to achieve functions requir-

ing large forces, hence they are not sufficient if we need to build large, fast, and strong applications. Biological systems are, for this reason, often consisting of the combinations of rigid and soft structures, and this aspect should be investigated more thoroughly in the near future [Culha and Iida, 2016]. As implied by such remaining challenges, the research of soft-material robots has been and will continue to be interdisciplinary. Many inspirations were given by biological studies, and enabling technologies were brought by material science and chemistry. It is absolutely essential to maintain the cross-disciplinary viewpoints in this research, and the overview of this research area should be updated in the future to account for the new development. Currently such accumulating knowledge is being communicated and archived through a community [Nurzaman et al., 2013b, Iida et al., 2016], which are open to those interested (For more details, please visit [www.softrobotics.org](http://www.softrobotics.org)).

The concept that functions and behaviors can be generated from the robot structures is a part of a larger concept known as embodied intelligence, which focuses on an important characteristic of biological systems, that is they exist as physical (embodied) entities in a real world. As a consequence, they have a particular shape of body morphology, tuned by evolution and developmental process, endowed with the necessary sensory and motor systems, and embedded within their ecological niches ([Pfeifer and Bongard, 2006, Pfeifer et al., 2007, 2014].

While robotic systems also exist as embodied entities in a real world, a distinctive difference between robotic and biological systems is biological systems are mainly composed of soft materials. In human, for example, the rigid skeleton comprises less than fifteen percent of overall body weight [Gropper and Smith, 2009]. More importantly, the use of soft materials have been indicated to have a large responsibility for the adaptivity, robustness, and resilience found in nature such as stabilization of the body, adaptation to an object's shape during grasping or coping with impact in walking [Pfeifer et al., 2014]. It can also be said that it is as if the morphology and materials of the biological systems, and their interaction with the environment, facilitate or take over some parts of the control and computation necessary to accomplish the tasks, which is why the phenomena are also referred to as morphological com-

putation. More specifically, morphological computation can be loosely defined as the exploitation of the body morphology, shape, material properties, and physical dynamics of a physical system due to its interaction with the environment to facilitate computation which can be applied to facilitate control or sensing in physically embodied systems ([Hauser et al., 2011, Fuchslin et al., 2013, Iida and Nurzaman, 2016], although it must also be noticed that the concept is also implementable in systems other than soft bodied robots, e.g. self-assembly of chemical microreactors [Fuchslin et al., 2013] or underactuated swimming robot with rigid body [Nurzaman et al., 2012].

The embodied intelligence concept blurs the line between the body and the brain, where the use of soft materials can be beneficial to facilitate control algorithms in many situations due their rich dynamics ([Hauser et al., 2011, Kuwabara et al.]. However, apart from the rich, exploitable, body dynamics of soft bodied robots, the role of the enormous plasticity of the brain, and how it should be related to the body dynamics that leads to a control architecture to realize adaptive and resilience behavior is also actively investigated. For example, the tight coupling between control structure and body morphology has been shown in hopping behavior [Marques et al., 2014, Nurzaman et al., 2014a, 2015, Kim et al., 2015b]. Inspired by biological evolution, efforts have also been made to co-discovery soft robot morphology and control [Rieffel et al., 2014, Joachimczak et al.].

Another concept related to embodiment and embodied intelligence is known as 'sensor morphology'. In biology, the term "sensor morphology" is defined as the morphology of an organism at the sensor level, whose variability may translate into variation in their physiological and ecological performance [Dangles et al., 2005]. It has been suggested that the understanding of the role of sensor morphology in biological systems, or to be more exact how it adapts to task-environment, may lead to an integrative view of machine perception through the understanding of several fundamental principles. As explained in [Iida and Nurzaman, 2016, Nurzaman et al., 2013a], the role involves: (1) physical conversion, filtering and amplification of stimuli through the morphology, e.g. ranging from sensors in real biological systems like crayfish



or crickets [Dangles et al., 2005, Mellon, 2012] or strain sensors used in soft-material robots [Culha et al., 2014a] (2) morphology for active sensing and sensory motor coordination. Sensing problems in nature are largely combined with motor function. It has been shown that through a mutual coupling of sensing and acting, a physical agent is able to obtain more structured sensory information, rather than 'passively' registering sensory information [Pfeifer et al., 2007] (3) Sensing through mechanical dynamics. A representative example is shown by [Iida and Pfeifer, 2006], where a dynamic four-legged robot with elastic feet and passive joints can derive its attractor states from its own mechanical dynamics due to the interaction with the environment (4) Adaptation over multiple timescales, or to be more exact the understanding of how a physically embodied system like animals or robots co-adapt their control, sensing and morphology over multiple timescales [Iida and Nurzaman, 2016]. Sensing in soft-material robots and the problem of sensor morphology adaptation are related in many ways as deformation of morphologies is the underlying driving force for biological systems to exploit morphologies for the sensing purposes.

The research field of soft-material robots is still in a nascent stage and it is difficult to predict where it goes in the long term. However, as outlined in the discussion above about the transversal issues, soft-material robotics touches the fundamental problems of robot designs and functions, more toward biologically plausible, self-organizing, and adaptive in complex and uncertain situations. The research directions and aspects shown in this chapter could help structuring the discussion toward such a long-term perspective.

Finally, for a sustainable and systematic development of the research field, it is of crucial importance to consider education and training of younger researchers and students. Soft-material robotics has also a unique characteristics where educational curricula and practices can be achieved quickly, economically, and broadly. There have been a considerable amount of knowledge and resources available [Yu et al., 2013, 2014, Rosendo et al., 2016, Holland et al., 2016], which should be exploited for further development of the field. For further updates, the authors encourage readers to join the community at [softrobotics.org](http://softrobotics.org).

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